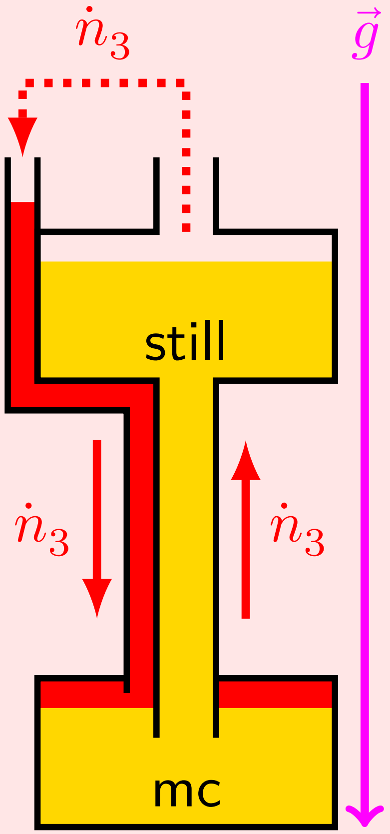
Néel Institute space cryogenics (G. Vermeulen, J. Vessaire)

with gravity

🟥 ^{3}He

🟨 ^{3}He-^{4}He



earth: most common dilution refrigerator

- gravity localizes phase separation interfaces of
  - liquid and vapor phases in still
  - concentrated (lighter) and dilute (heavier) phases in mixing chamber

any gravity: space or goniometer

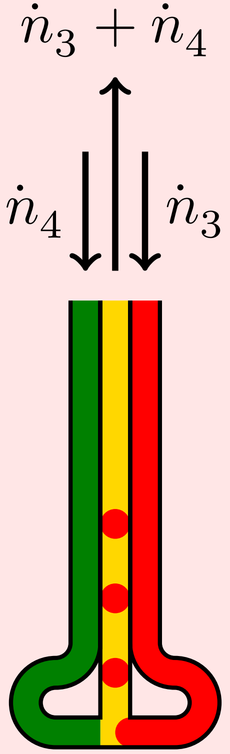
- capillary forces play the role of gravity
  - radius of the tubes smaller than the capillary radius of ^{3}He droplets
  - 2-phase flow in laminar part of mixture return tube
  - 1-phase flow in turbulent part of mixture return tube

any gravity

🟥 ^{3}He

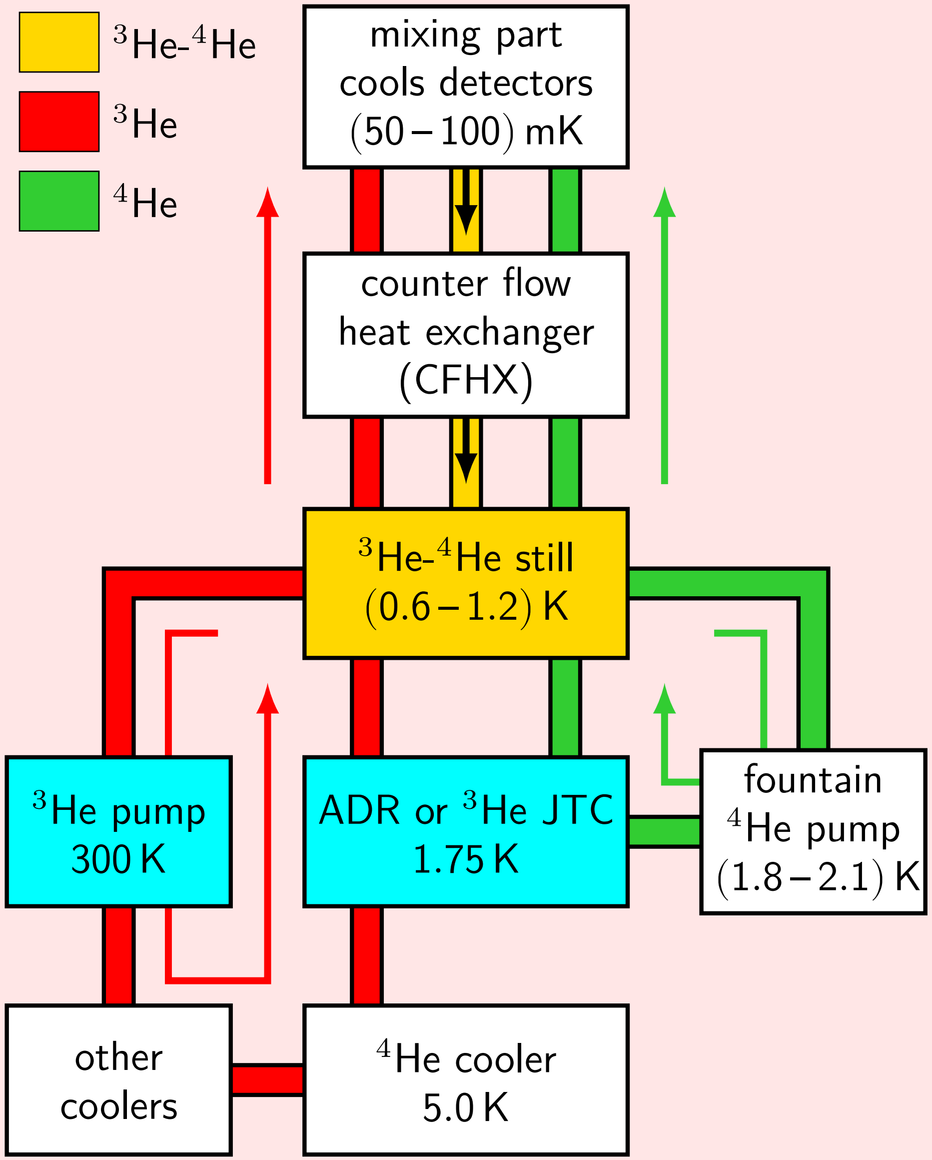
🟨 ^{3}He-^{4}He

🟩 ^{4}He



Néel Institute space activities

space: capillarity instead of gravity



CCDR in cooling chain

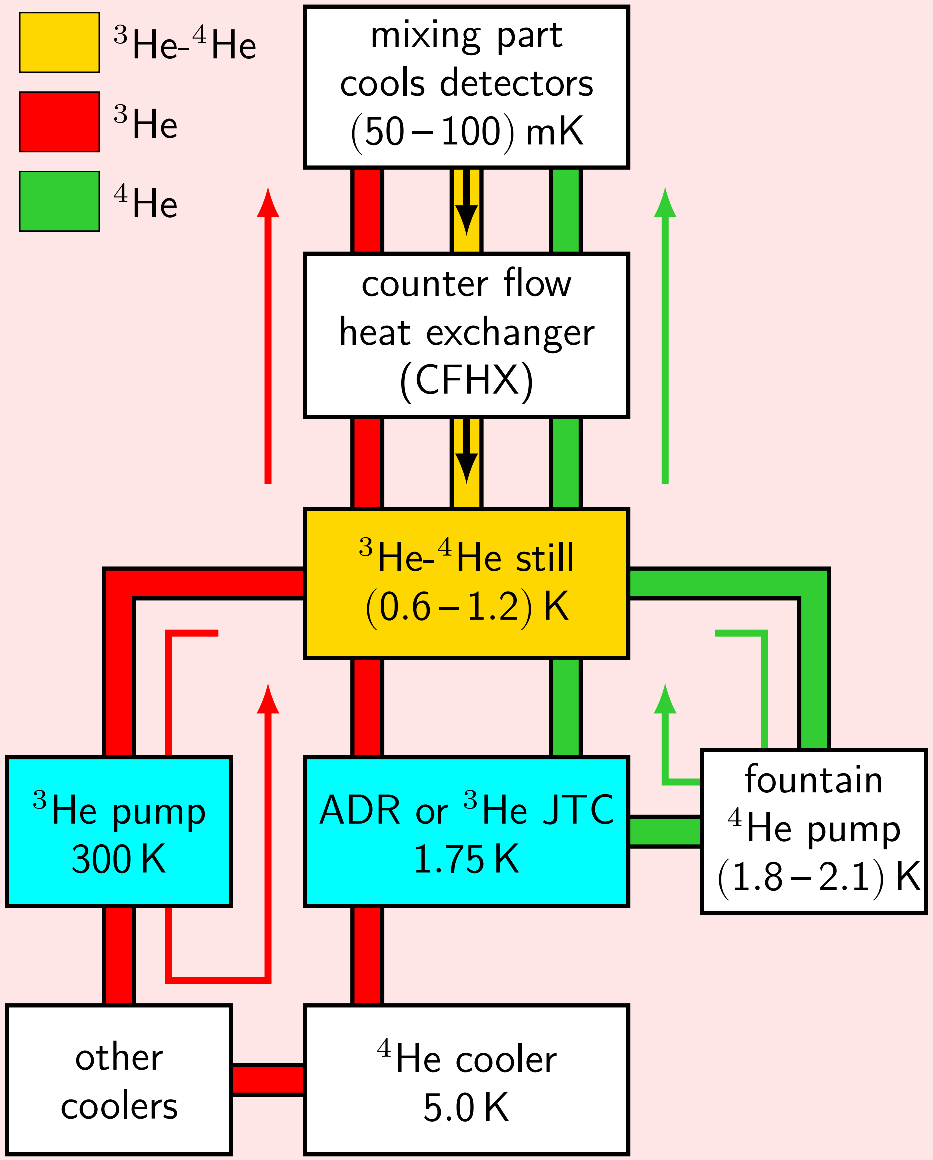
- dilution refrigerator proper is mixing part + counterflow heat exchanger
- + isotope separator is ^{3}He-^{4}He still + fountain pump to get a flow of pure liquid ^{4}He and and a flow of almost pure ^{3}He vapor
- external 1.75 K cooler to absorb the heat load of the circulating ^{3}He and ^{4}He
- external ^{3}He circulation pump
- rest of cooling chain

Néel Institute space cryogenics activities

- construction and test of demonstration model dilution refrigerator (X-IFU specs):
  - thermal test of CCDR support structure having dimensions compatible with future vibration test support structure
  - experimental check of the thermal CCDR model used to design the support structure
- knowledge transfer to and collaboration with D-SBT (CEA)
  - work on design to make and test a simplified zero gravity isotope separator device in a cryostat at the CEA
  - participation of D-SBT in the test of the X-IFU CCDR demonstration model
  - sharing CCDR physics and computer program implementing the thermal model
- D-SBT/CNES contract: design proposal for engineering model of isotope separator for CCDR

Zero gravity CCDR in simplified cooling chain

space: capillarity instead of gravity



🟨 ^{3}He-^{4}He
🟥 ^{3}He
🟩 ^{4}He

mixing part cools detectors (50 – 100) mK

counter flow heat exchanger (CFHX)

^{3}He-^{4}He still (0.6 – 1.2) K

^{3}He pump 300 K

ADR or ^{3}He JTC 1.75 K

fountain ^{4}He pump (1.8 – 2.1) K

other coolers

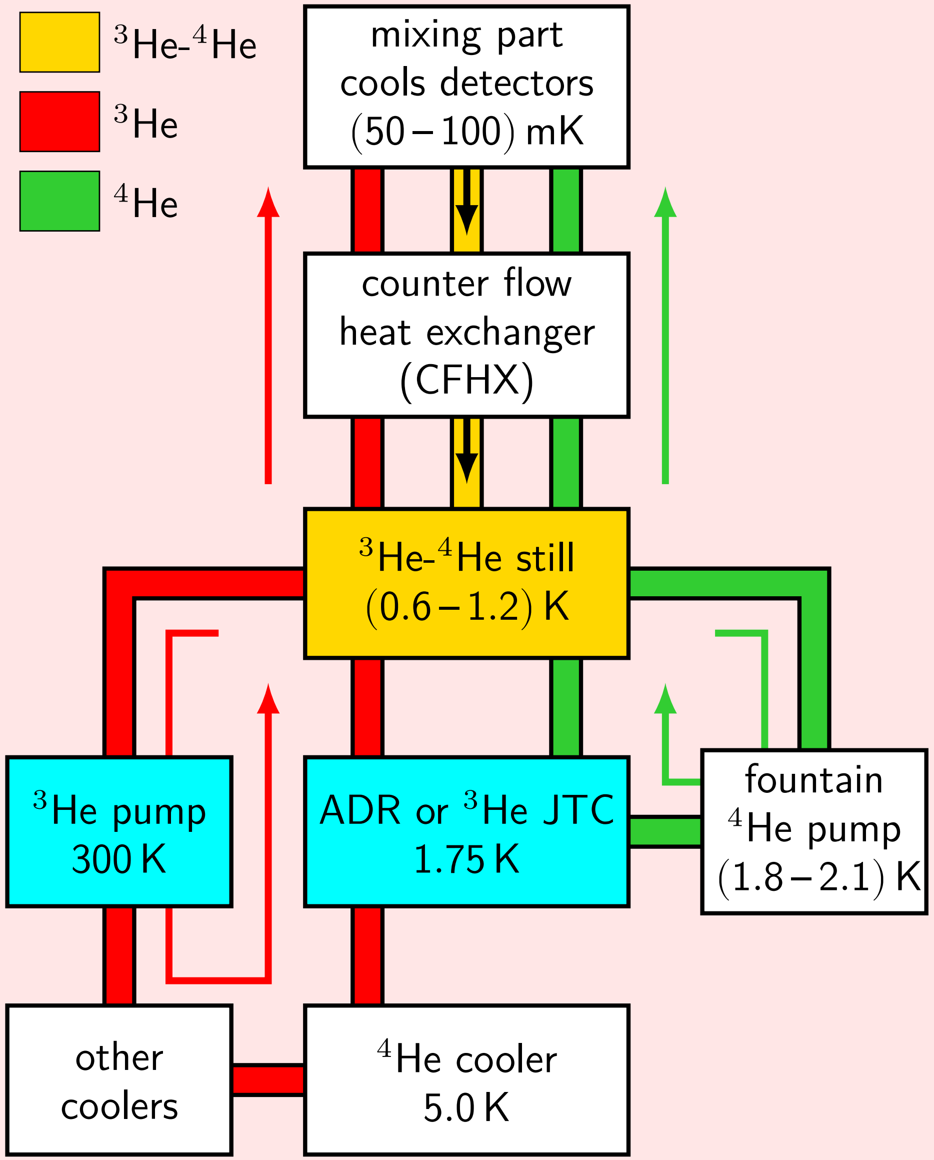
^{4}He cooler 5.0 K

thermal-mechanical design issues

- CFHX and mixing part tuning
  - $\dot{Q}_{\text{lift}} \propto$ ^{4}He and ^{3}He circulation rates $\dot{n}_4$ and $\dot{n}_3$
- direct CCDR interfaces:
  - ^{3}He circulation pump
  - ^{3}He Joule-Thompson (JTC)
- ^{4}He circulation $\dot{Q}_{\text{load}}$ on
  - ADR or ^{3}He JTC
  - lower T_{still} implies lower $\dot{Q}_{\text{load}}$
- ^{3}He circulation $\dot{Q}_{\text{load}}$ on
  - other coolers
  - ^{4}He cooler
  - ADR or ^{3}He JTC
- CCDR support struts and links to focal plane (launch)

Zero gravity CCDR in simplified cooling chain

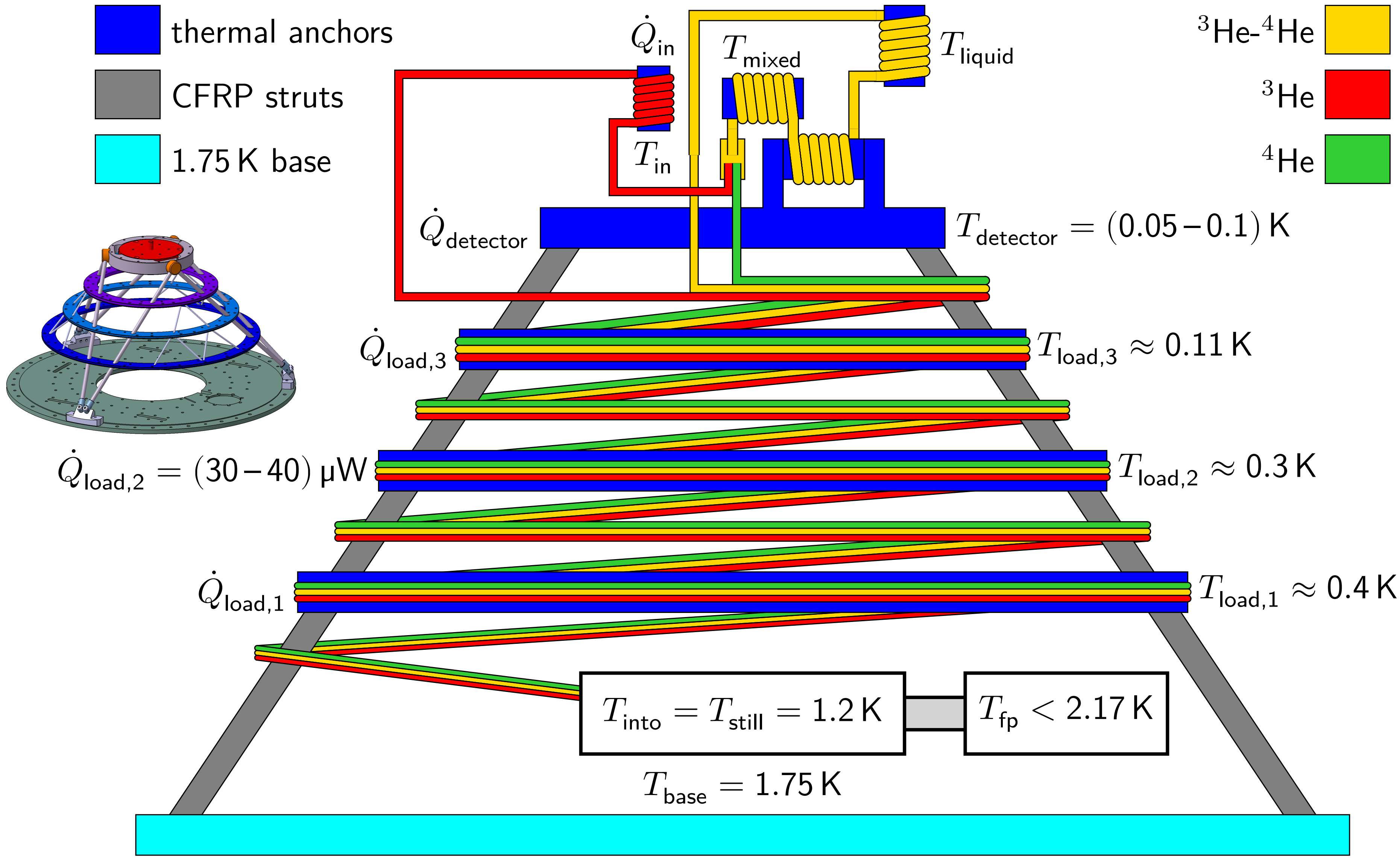
space: capillarity instead of gravity



thermal model

- input:
  - focal plane temperature and heat load to mixing part
  - instrument heat load to counterflow heat exchanger
- CCDR output:
  - ^{3}He circulation rate
  - ^{4}He circulation rate
- implies cooling chain output:
  - cooling power 1.75 K stage
  - ^{3}He circulation pump specs

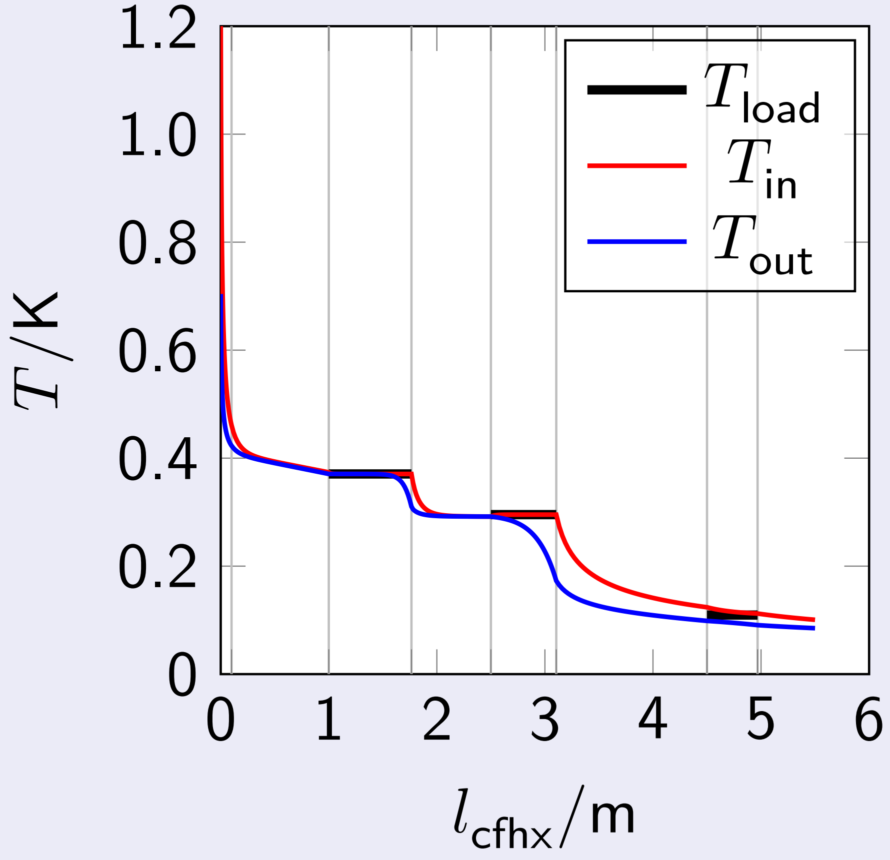
All DM/EM CCDR model parts



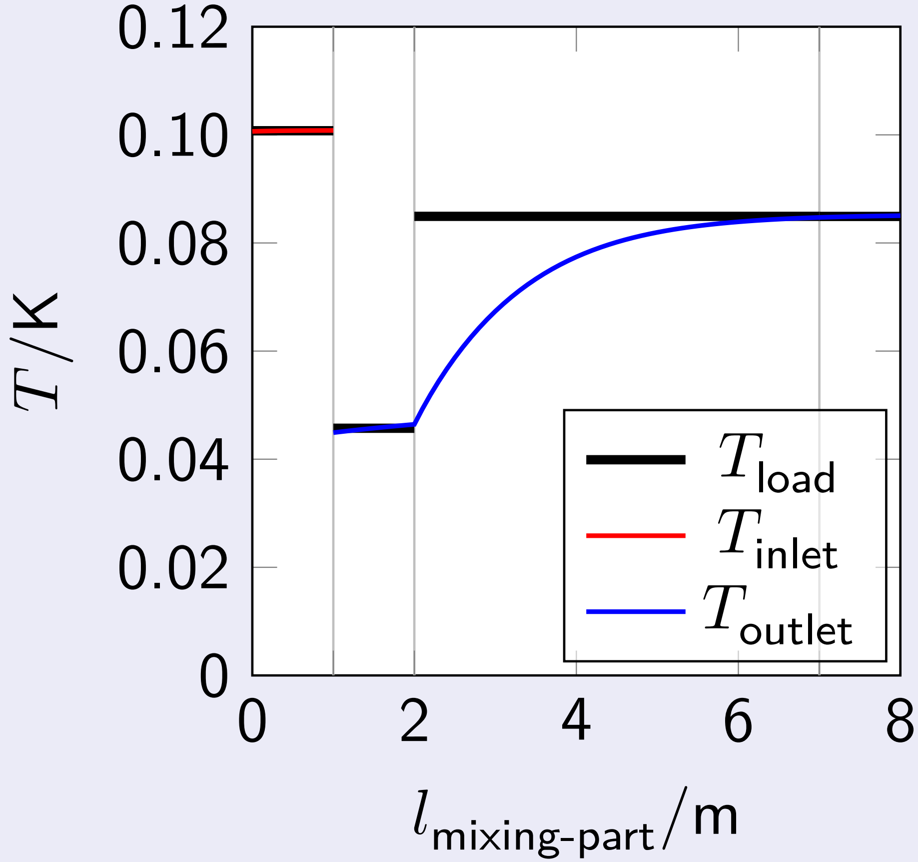
thermal model for all CFRP struts and all CCDR parts below T_{still}

CCDR temperatures for $\dot{Q}_{\text{detector}} = 4\,\mu\text{W}$ (LiteBIRD)

CFHX sections



Mixing part inlets and outlets



- $l_{\text{cfhx}} < 1\,\text{m}$: viscous dissipation
- enough CFHX surface at T_{load}

- mixing at $l_{\text{mixing-part}} = 1\,\text{m}$
- $T_{\text{detector}} \approx 0.085\,\text{K}$

Relative merits of ADR and CCDR

ADR versus CCDR

- ADR wins on TRL and on competition
- ADR wins on efficiency
    - ADR cycle approaches ideal Carnot cyle
    - CCDR is less efficient because of ^{3}He Fermi-Dirac statistics
- CCDR can win on mass $< 4\,\mathrm{K}$
    - propagates back into system (lighter is easier for vibrations and also for thermal isolation)
- CCDR cooling is intrinsically continuous
    - multi-stage ADR approximates continuous cooling by clever cycling of magnetic fields
- CCDR does not require changing magnetic fields
    - CMB community likes CCDR for detector stability